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GEOLOGY OF THE SPERRY MINE, DES MOINES
COUNTY, IOWA.

Iowa State University of Science and Technology
Ph.D., 1964
Geology

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GEOLOGY OF THE SPERRY MINE, DES MOINES COUNTY, IOWA

by

Lyle Vernon Archie Sendlein

A Dissertation Submitted to the
Graduate Faculty in Partial Fulfillment of
The Requirements for the Degree of
DOCTOR OF PHILOSOPHY

Major Subjects: Geology
Soil Engineering

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Dean of Graduate College

Iowa State University
Of Science and Technology
Ames, Iowa

1964

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INTRODUCTION

The purpose of this study is to investigate the geology of the gypsum bed from which production is obtained at the Sperry Mine of the United States Gypsum Company with respect to stratigraphic occurrence, regional and local structural setting, nature of the gypsum bed, and origin of the deposit.

The mine is located approximately eleven miles north of the city limits of Burlington, Iowa, Des Moines County, on U. S. highway 61 (NE $\frac{1}{4}$ NW $\frac{1}{4}$ Sec. 3 T71N R2W). This places the mine approximately two miles south and one mile west of the rural community of Mediapolis, Iowa.

The gypsum occurs in the Spring Grove member of the Devonian Wapsipinicon formation at a depth of 610 feet below the surface. The Wapsipinicon formation is composed of limestone, dolomite, gypsum and shale, and rests unconformably on the Ordovician Maquoketa shale.

The regional dip is approximately six feet per mile to the southwest and locally the strata are folded in an en-echelon pattern of doubly plunging anticlines and synclines with their axes trending northwest-southeast. These structures as mapped on the top of the Mississippian contain approximately 100 feet of closure. The gypsum deposit is located near the crest of one of the anticlines. Bore hole information on a regional basis indicates that the sulfate member extends to the southwest and that anhydrite dominates over gypsum down dip.

The gypsum bed is overlain and underlain by dolomite. The upper contact is sharp whereas the lower boundary is gradational. The thick-

ness of the bed is variable, ranging from stringers measuring less than a centimeter to a bed slightly less than 4.5 meters. The gypsum bed is divided into two horizontal units (upper and lower gypsum) by a carbonate lamina. The gypsum exposed in the mine represents the upper 3.0 meters of the bed. There are lenses of black dolomite and satinspar present in the upper gypsum, and anhydrite lenses are present in the lower portion of the upper gypsum and the upper portion of the lower gypsum. Dolomite bodies of uneven dimensions and a quartz nodule horizon constitute minor irregularities of the gypsum bed.

Irregular laminations caused by interlayering of thin dolomite stringers and gypsum produce a bedded structure commonly referred to in the literature as "banding". The laminations are faintly observable in the upper portion of the gypsum bed but become more prominent toward the bottom of the unit. The laminations display a pseudo-fold form undescribed in the literature.

In light of current theories and data gathered by the writer, two aspects of the origin of the Sperry gypsum deposit must be considered. Evidence indicates that gypsum is secondary after anhydrite and therefore must be a hydration product of the anhydrite which it replaces. The origin of the sulfate deposit as a whole, however, is questionable since the chemical nature of the primary deposit cannot be determined.

REVIEW OF THE LITERATURE

The first study of the geology of this area was in 1893 when Keyes described the geology of Des Moines County. His investigation, which was part of the annual report of the Iowa Geological Survey, includes all borings and outcrops available at the time. Since then only isolated areas have been geologically studied.


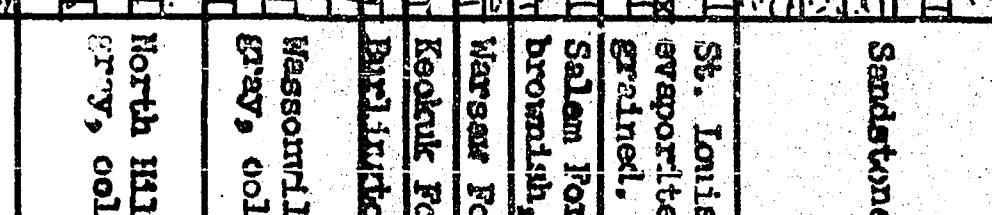
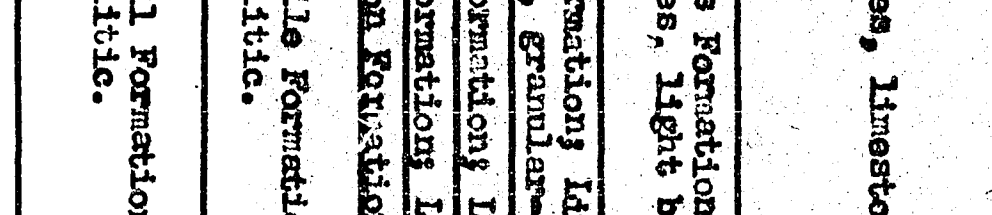
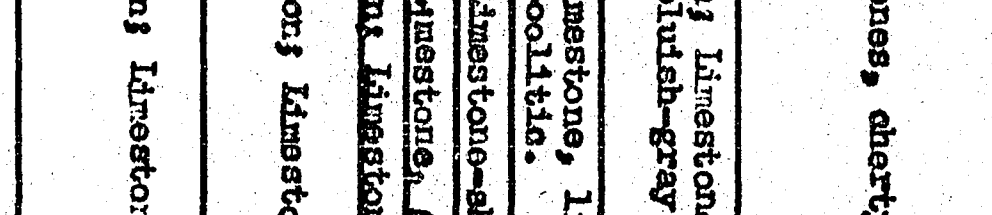
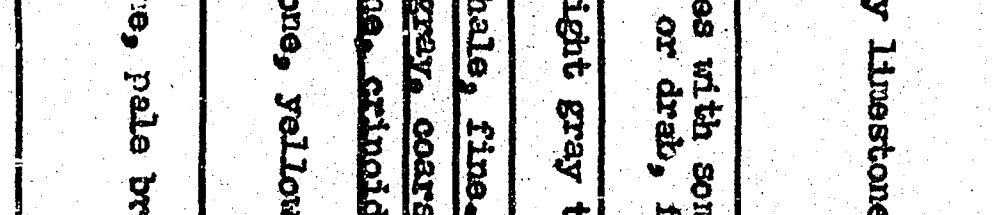
A generalized stratigraphic column is presented in Figure 1. A detailed description of each rock unit can be obtained elsewhere in the literature and will not be repeated here (Kansas Geological Society, 1935; Agnew, 1955; Laudon, 1931).

Gypsum occurrence is extensive in the United States (Adams, 1904; Withington and Jaster, 1960) and elsewhere in the world. The major sulfate deposits in Iowa occur in Devonian, Mississippian and Permian (?) strata. A single occurrence of Permian (?) gypsum is located at the surface in the Fort Dodge vicinity. Mississippian and Devonian sulfates occur in the subsurface in lenticular or intermittent deposits distributed over approximately the southern half of the state. Mississippian gypsum outcrops in south central Iowa along the Des Moines River.

Deer et al. (1962) has described the chemical and physical properties of gypsum and many other authors have described gypsum as observed in thin sections (Stewart, 1949, 1951a, 1951b; Brown, 1931; Bundy, 1956; Goldman, 1952; and Ogniben, 1955, 1957a).

Gypsum occurs mainly in massive and bedded deposits as alabaster or rock gypsum, a compact granular rock, and as selenite, a transparent

Figure 1. Generalized stratigraphic column

MISSISSIPPIAN			PENNSYLVANIAN	QUATERNARY	SYSTEM
UNDERHOOK		OSAGE	MERAMEC	DES MOINES	SERIES
CHOUTEAU	HAMPTON				GROUP
					DESCRIPTION Fill and Drift; varies in color from reddish brown to blue gray, texture varies from well sorted sands to poorly sorted material, clay size to boulders. Sandstones, limestones, cherty limestones St. Louis Formation; limestones with some evaporites, light bluish-gray or drab, fine-grained. Salem Formation; limestone, light gray to brownish, granular-oolitic. Warsaw Formation; limestone-shale, fine. Keokuk Formation; limestone, gray, coarse. Burlington Formation; limestone, crinoidal. Massonville Formation; limestone, yellowish-gray, oolitic. North Hill Formation; limestone, pale brownish gray, oolitic.
					THICK- NESS (ft)
					0-300
					6-700
					50-250
					2-3
					70
					70
					0-150
					10
					3-20

		DEVONIAN	SILURIAN	ORDOVICIAN
	KINDERHOOK	ERIAN	NIAGARAN	CINCINNATI
	CHOUTE	HANNIBAL		RICHMOND
North Hill Formation; Limestone, pale brownish gray, oolitic.				
Prospect Hill Formation; Siltstone, buff.	0-20			
McCraney Formation; Limestone and dolomite, sublithographic.	0-12			
English River Formation; Siltstone, buff.	10			
Harpes Hill Formation; Shale, greenish to dark brown, silty-dolo. etc.	0-300			
Lime Creek Formation; Dolomite, greenish-gray to buff, silty.	9			
Cedar Valley Formation, Rapid Member; Limestone, buff, sublithographic.	55-60			
Cedar Valley Formation, Solon Member; Limestone, gray sublithographic, fossils.	58-61			
Wapsipinicon Formation, Darroport Member; Limestone, gray lithographic, some evaporites.	16-18			
Wapsipinicon Formation, Spring Grove Member; Dolomite, buff-brown, fine grained, gypsum and anhydrite.	23-40			
Wapsipinicon Formation, Fairwood Member; Dolomite, greenish-gray, fine-grained, some evaporites present.	17-22			
Dolomite, yellowish to white, very porous in places, sometimes granular.	0-325			
Magnoketa Formation; Shale, very dark green to gray, very fine-grained, fossiliferous in upper half.	160-235			

variety. Satinspar is a fibrous variety of gypsum which occurs in veins. Gypsum is commonly associated with anhydrite and halite and considered by most authors to be part of a group of rocks referred to as evaporites.

Gypsum and anhydrite have been found to occur in four major stratigraphic sequences in the United States (Krumbein, 1951):

1. marine-sulfate-marine
2. marine-sulfate-red beds
3. red beds-sulfate-marine
4. red beds-sulfate-red beds

Sequences two, three and four above are commonly associated with basin-margin deposits whereas sequence one is considered a basin-center deposit. The deposit at Sperry has a stratigraphic sequence similar to number one above. The marine-sulfate-marine sequence is not common and according to Krumbein (1951) occur only in intracratonic basins.

Internal structures of various kinds have been observed in gypsum beds. Grabau (1920) described small (one centimeter radius) intensely folded gypsum lamina as enterolithic. Ogniben (1957a) has described small folds (less than one meter in radius) as swelling structures. Laminations in gypsum and anhydrite, referred to as "banding" by many authors, are produced by interlayering of the sulfate and dolomite or organic matter (Udden, 1924; Withington, 1961). The laminations are uneven and have been termed pinch and swell structures by many authors and boudinage by Riley and Byrne (1961).

Fold forms observed in sulfates have been described by Pallister et al. (1962), Wilder (1917), and Ogniben (1957a). The folds described by Pallister et al. are considered by them to be the result of folding

caused by forces external to the gypsum bed. Wilder's (1917) description of doming of gypsum at the surface is considered by him to be the result of a recrystallization mechanism. Ogniben (1957a) has called the folds he observed in Sicilian deposits "swelling structures", considers the swelling to be penecontemporaneous with the gypsum formation (personal communication), and finds that the displacement is not transferred to the gypsum above but absorbed in the interlayered marls.

Mechanisms of folding have been discussed by DeSitter (1956), Hills (1963), Belousov (1962), and most recently by Donath and Parker (1964). All agree that the geometry and internal features of folds reflect the mechanisms that produce folds. They have classified folds according to their geometry and mechanism of formation. Donath and Parker (1964) grouped them into three classes: flexural, passive and quasi-flexural folds, separated on the following basis:

"Flexural mechanisms are dependent on the presence of mechanical anisotropy; passive mechanisms operate when anisotropy is absent or ineffective. As the ductilities of the involved rocks increase, the effect of layering in the folding process decreases.

Flexural folding represents a true bending of layers and can be produced by slip between layers, flexural slip, or by flow within layers, flexural flow. Passive folding reflects relative displacements of layer boundaries by flow or slip across the boundaries; the layering does not control the configuration of the deformed mass---it merely reflects the deformation. Passive mechanisms are designated passive flow and passive slip. Where irregular flow occurs within and across layers, certain layers are flexed in response to passive behavior in the associated rocks. This gradational mechanism is called quasi-flexural folding: the geometry and more obvious features of the fold are flexural in general aspect, but the overall behavior is predominantly passive. Individual fold mechanisms are not mutually exclusive but may operate singly or in combination to produce folds."

Figure 2. Fields of folding related to mean ductility and ductility contrast. From Donath and Parker (1964, page 50)

Figure 3. Stress distribution in a rectangular member due to bending. From Belousov (1962, page 545)

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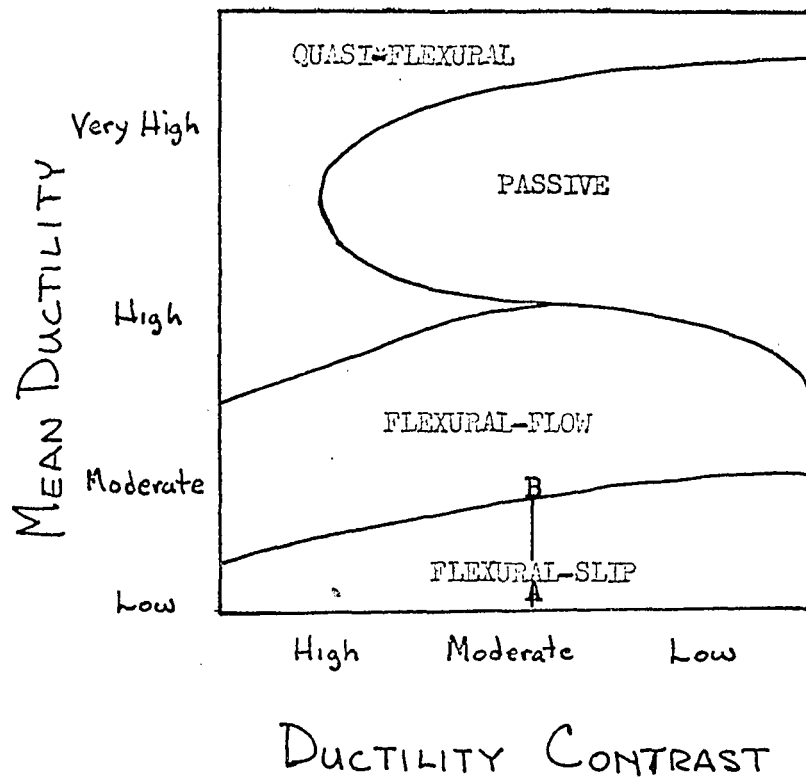
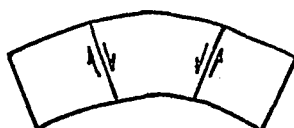
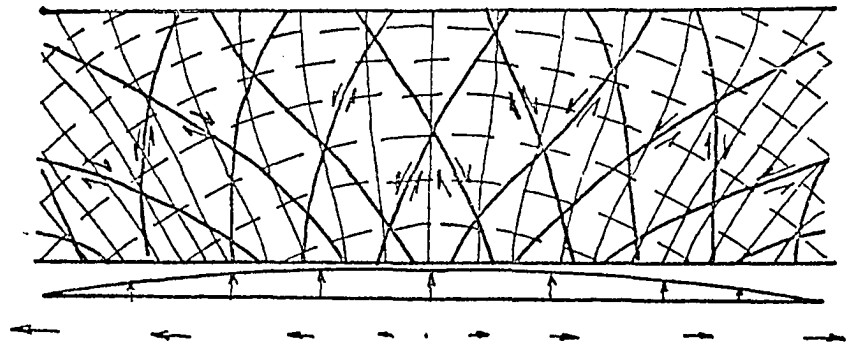
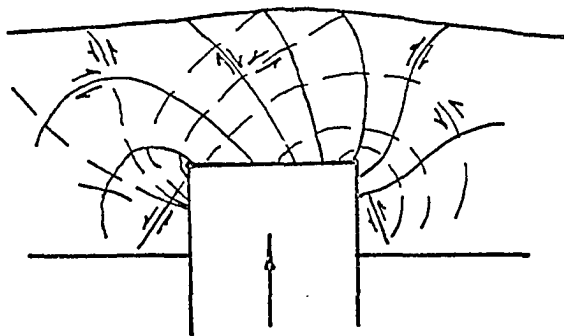

 σ_{max}

 τ_{max}

Figure 4. Stress system consisting of variable vertical and shearing stress along bottom of block. From Hafner (1951, plate 1)

Figure 5. Orientation of shearing surfaces on a plastic model intruded by a die. From Belousov (1960, page 1262)



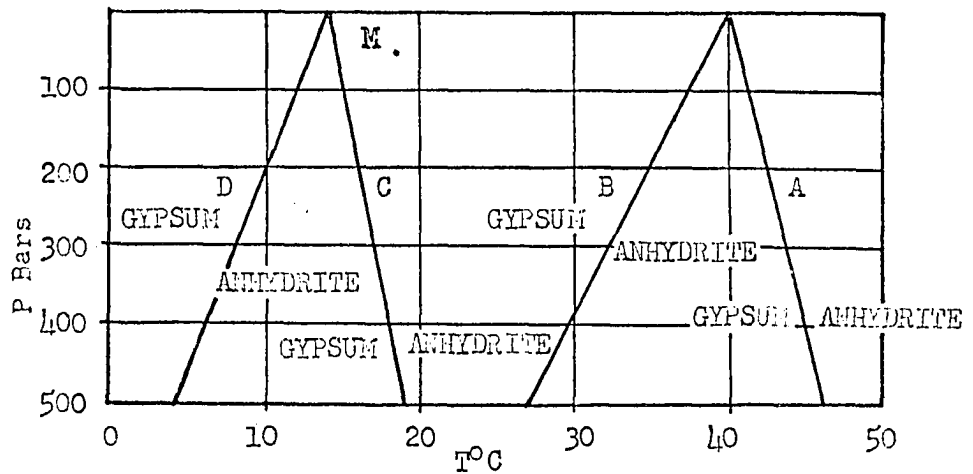
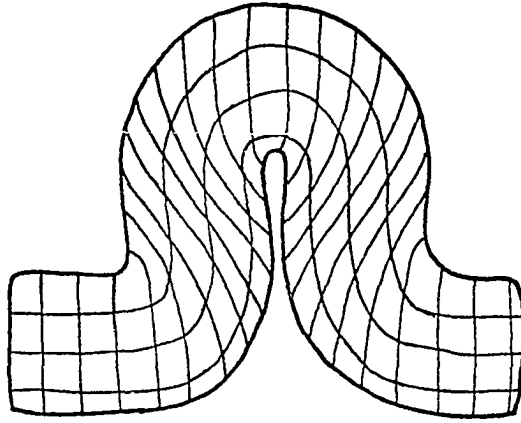
--- σ_{max}
— σ_{min}
— τ_{max}



— τ_{max}

Figure 6. Folded pack of paper sheets illustrating pure concentric folding. From DeSitter (1956, page 181)

Figure 7. Pressure temperature relationships for the $\text{CaSO}_4 \cdot \text{H}_2\text{O}$ in water and a saturated NaCl solution. From MacDonald (1953)



Curve A - Same pressure acting on all phases, in presence of pure H_2O

Curve B - Rock pressure acting on solid phases, hydrostatic pressure acting on pure H_2O

Curve C - Same pressure acting on all phases in presence of saturated NaCl solution

Curve D - Rock pressure acting on solid phases, hydrostatic pressure acting on saturated NaCl solution

A fold form which closely approximates that observed in the mine is found in the Triassic shales of New South Wales. An illustration of this form is shown on page 69 of Hills' (1963) "Elements of Structural Geology", and he described them as "superficial folds and thrusts due to the expansion of clay and shale on hydration during weathering."

The occurrence of extensive sulfate deposits poses a problem for which an answer has not been agreed upon. Primary deposition of anhydrite or gypsum has been proposed by many authors (Branson, 1915; Sloss, 1953; Briggs, 1958; Krumbein, 1951; Dellwig, 1955; Scruton, 1953; and Landes, 1963). Others have shown that alteration of pre-existing rocks can produce the two minerals (McCormack, 1926; Conly and Bundy, 1958; and Bundy, 1956).

The earliest concept proposed on the origin of sulfate deposits included an evaporating environment combined with a shallow basin restricted from the open sea by an offshore bar. Evaporation of the sea water increased the salt concentration and the sulfates were precipitated. The "bar theory" has been modified by many authors and is currently accepted in one form or another as the mode of formation of evaporites.

The evaporite association is composed of limestone, dolomite, anhydrite, gypsum, halite (rock salt), and polyhalite (Pettijohn, 1957). Examples of rock suites containing all members of the association are rare.

Normal sea water contains in solution all the components of the above rocks. Upon evaporation all of these will precipitate out of

solution according to their solubility. The order of precipitation would be: limestone, dolomite, gypsum or anhydrite, halite, polyhalite and the very soluble bitterns or remnants.

Several problems confront the evaporation hypothesis. They are:

1. The presence of great thicknesses of anhydrite deposits.
2. The absence of halite within and stratigraphically above or below the sulfates.

As a consequence of these problems very intricate mechanisms have been developed to explain the evaporation hypothesis (Sloss, 1953; Dellwig, 1955; Branson, 1915; and Landes, 1963).

The alteration of pre-existing rocks to produce extensive sulfate deposits by replacement has not been generally accepted. Bowels and Farnsworth suggested this mechanism as a possibility in 1925. Very few investigators have supported this hypothesis with data, however Bundy (1956) considered this as a possible explanation for the Indiana deposits. He showed through thermodynamic calculations that limestone could react with a ground water rich in magnesium and sulfate to produce anhydrite and dolomite spontaneously at standard conditions. He supported this with some petrographic evidence.

It is generally accepted that the alteration of anhydrite to gypsum or vice versa will take place as a near-surface reaction. Conly and Bundy (1958) proposed a gypsification mechanism which would convert anhydrite to gypsum through ions, (K^+ , Na^+ , NH_4^+ , Mg^{++} , Fe^{++} , H^+ , Ca^{++} , and $SO_4^{=}$), available in ground water. McCormack (1926) proposed primary deposition of gypsum followed by dehydration to anhydrite upon

lithification; however, his studies show that pressure alone will not induce dehydration but that the addition of heat is needed. MacDonald (1953) investigated the effect of pressure and dissolved solids on anhydrite, and found that with equal pressure on the solid and pure liquid there was very little effect. A differential pressure ratio approximately 2.4 times greater on the solid phase caused a lowering of the critical transition temperature between anhydrite and gypsum to 30 degrees centigrade at 400 bars pressure on the solid phase. He also showed that in a saturated solution of NaCl the transition temperature was lowered to 14 degrees centigrade at standard conditions. His results are presented in Figure 7 and discussed in the appendix.

Volume change associated with the hydration of anhydrite is dependent on the nature of the replacement mechanism. Opinions on the amount of change range from 10% decrease all the way up to a 60% increase in volume. Farnsworth (1924) showed that an approximate 10% increase in total volume (anhydrite plus water) resulted when she dehydrated 1000 grams of gypsum. Using her data it can be shown that there is an actual decrease of 28.3 cc per mole of anhydrite in the dehydration process. Thin section evidence such as anhydrite euhedra cut by gypsum with no apparent displacement of either anhydrite fragment has been used by Goldman (1952) as evidence for a no volume change reaction. Grabau (1920) and King (1947) both cite the pinch and swell structure as evidence for volume increase during hydration. Bundy (1956) explains volume expansion through directional crystallization in vein formation.

METHOD OF STUDY

The study was conducted by collecting field data and specimens, compiling the field data and studying the specimens by laboratory techniques, and interpreting the results.

The data were gathered by : 1. drilling eighteen bore holes on 400 foot spacing around the periphery of the Sperry mine, 2. mapping the gypsum as exposed in the mine walls, 3. describing the gypsum megascopically and microscopically, and 4. performing laboratory analyses on specimens collected.

The drilling program was conducted during the summer and winter of 1961-62. Six-inch holes were drilled from the surface to the Ordovician Maquoketa shale. One hole was cored from the top of the Devonian (?) Maple Mill shale to the Ordovician but most holes were cored from the top of the Devonian Lime Creek formation to the Ordovician. The cores were logged and stored for future use. From bore hole information the writer was able to construct structure contour maps of the local area (Figures 8, 9, 10 and 11) using the tops of the Cedar Valley and Wapsipinicon formations, respectively, as datum horizons.

In order to observe and study structure and occurrence as exposed in the mine along the walls, pillars and roof, gypsum dust which had accumulated on the walls had to be removed. The mine was then mapped on a scale of one inch to ten feet. The resulting map cannot be released at this time.

Thin sections were made from specimens considered to be representative of the various units exposed in the mine. Each thin section was studied with the petrographic microscope according to the following procedure:

1. all minerals were identified
2. grain shape, size and orientation was described
3. paragenesis was worked out.

Two types of laboratory analyses were performed, both designed to detect the presence of quartz in the gypsum units. Three gypsum samples were dissolved in concentrated hydrochloric acid and did not produce an insoluble residue and therefore no quartz. X-ray analyses of the various units indicated no evidence of quartz or any other mineral not observed in thin section.

GENERAL GEOLOGY

Since Keyes described the general geology in 1893, very little has been published on this area. A guide book compiled by the Kansas Geological Society in 1935 covers this area and includes stratigraphic descriptions, isopach maps and structure contour maps for the major formations present. The generalized stratigraphic column presented in Figure 1 was taken primarily from this source.

Surface Geology

Fleistocene till and alluvium comprise the major units exposed at the surface. Rocks which crop out in the area are Pennsylvanian in the northern portion of the county and Mississippian in the southern half. Several known outcrops of Devonian (?) Maple Mill shale are also present. Outcrops of Mississippian strata occur along the bluffs of the Mississippi River, which borders the county on the east.

Subsurface Geology

Stratigraphy

Approximate stratigraphic thicknesses in the local area to the top of the Maquoketa shale are as follows:

Pleistocene till.....	100-300 feet
Mississippian.....	45 feet
Devonian (?) Maple Mill.....	300 feet
Devonian Lime Creek.....	10 feet
Devonian Cedar Valley.....	120 feet
Devonian Wapsipinicon.....	75 feet

The buried bedrock surface is dissected by deep steep-walled valleys of probably pre-Pleistocene age. The bedrock on the buried upland surface is Mississippian; the Devonian (?) Maple Mill shale and occasionally the Devonian Cedar Valley limestone constitute the bedrock surface in the deep buried valleys.

The thickness of the glacial till varies from a few feet to approximately 100 feet on the upland surfaces and up to 300 feet in the buried valleys.

The Mississippian limestones are part of the Kinderhook series. In places they have been removed by erosion during the formation of the buried valleys, and also thinned on the upland surface to an average thickness of 45 feet.

The Devonian (?) Maple Mill shale has a thickness of 300 feet where overlain by Mississippian limestone. The shale is absent in isolated areas located beneath the bottom of deep valleys.

The Devonian Lime Creek dolomite and Cedar Valley limestone are generally present in full thickness.

The Wapsipinicon formation is composed of five members, of which only the upper three are present in this area. They are from youngest to oldest: Davenport limestone, Spring Grove dolomite, and Kenwood shale. The Otis and the Coggan members are absent.

The Spring Grove member has an overall thickness of approximately 35 feet. The gypsum is located near the middle of this member. The Spring Grove member is fine-grained, thinly laminated, saccharoidal, buff to brown dolomite, and contains abundant steeply-dipping, calcite-

filled fractures. The top of the gypsum bed forms a sharp stratigraphic break with the dolomite and the lower contact is gradational with dolomite below. The contact of the Spring Grove member with the underlying Kenwood shale is also gradational.

Structure

The study area is located near the Mississippi arch (Howell, 1935) between the Forest City Basin to the southwest and the Illinois Basin to the east. The axis of the arch roughly parallels the Mississippi River (Howell, 1935). The regional dip to the west is 6 feet per mile and to the east is 12 feet per mile.

As a result of recent studies by Parker of the Iowa Geological Survey (personal communication) on a sub-regional basis and by the writer on a local scale, smaller folds have been found superimposed on the regional structure. These folds have a northwest-southeast trend (Figure 8) and display an enechelon pattern of doubly plunging anticlines and synclines. The mine is situated near the crest of one of these anticlines.

Contour maps constructed on top of the Cedar Valley formation (Figures 8, 9 and 10) and the Wapsipinicon formation (Figure 11) display the local structure.

During the mapping of the mine, joints were observed in the gypsum as smooth vertical faces. From the small number of joints observed in the mine a vertical joint set is postulated with one group having an attitude of north eight to twelve degrees east and the other north forty

five degrees east. Where the black dolomite lense is absent joints observed in the dolomite roof conform to this joint set.

Figure 8. Structure contour map on top of the Cedar Valley formation, 25 foot contour interval. This map includes all of Des Moines County and most of Louisa County

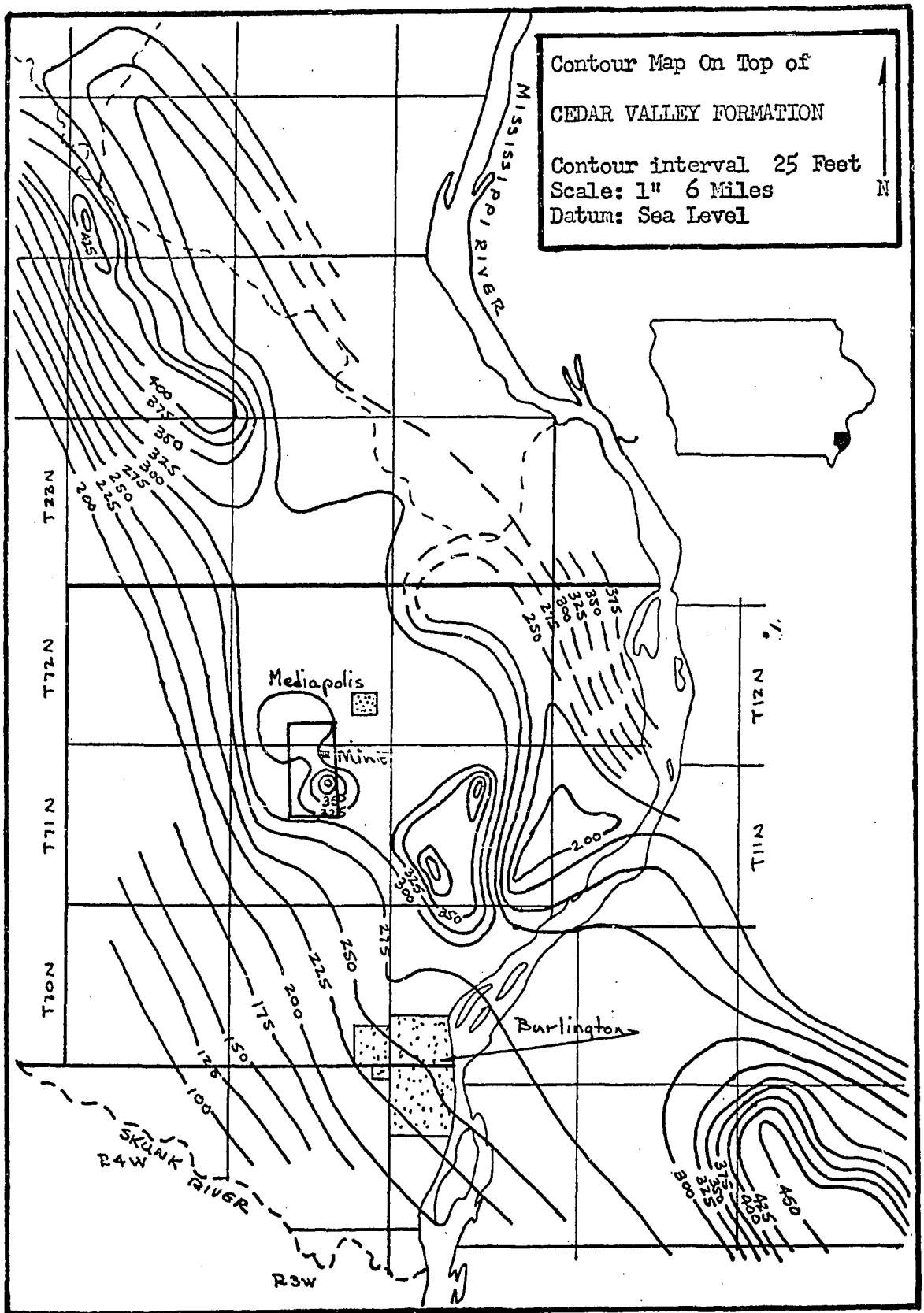


Figure 9. Structure contour map on top of the Cedar Valley formation, 5 foot contour interval. The area covered in this map is outlined in red in Figure 8

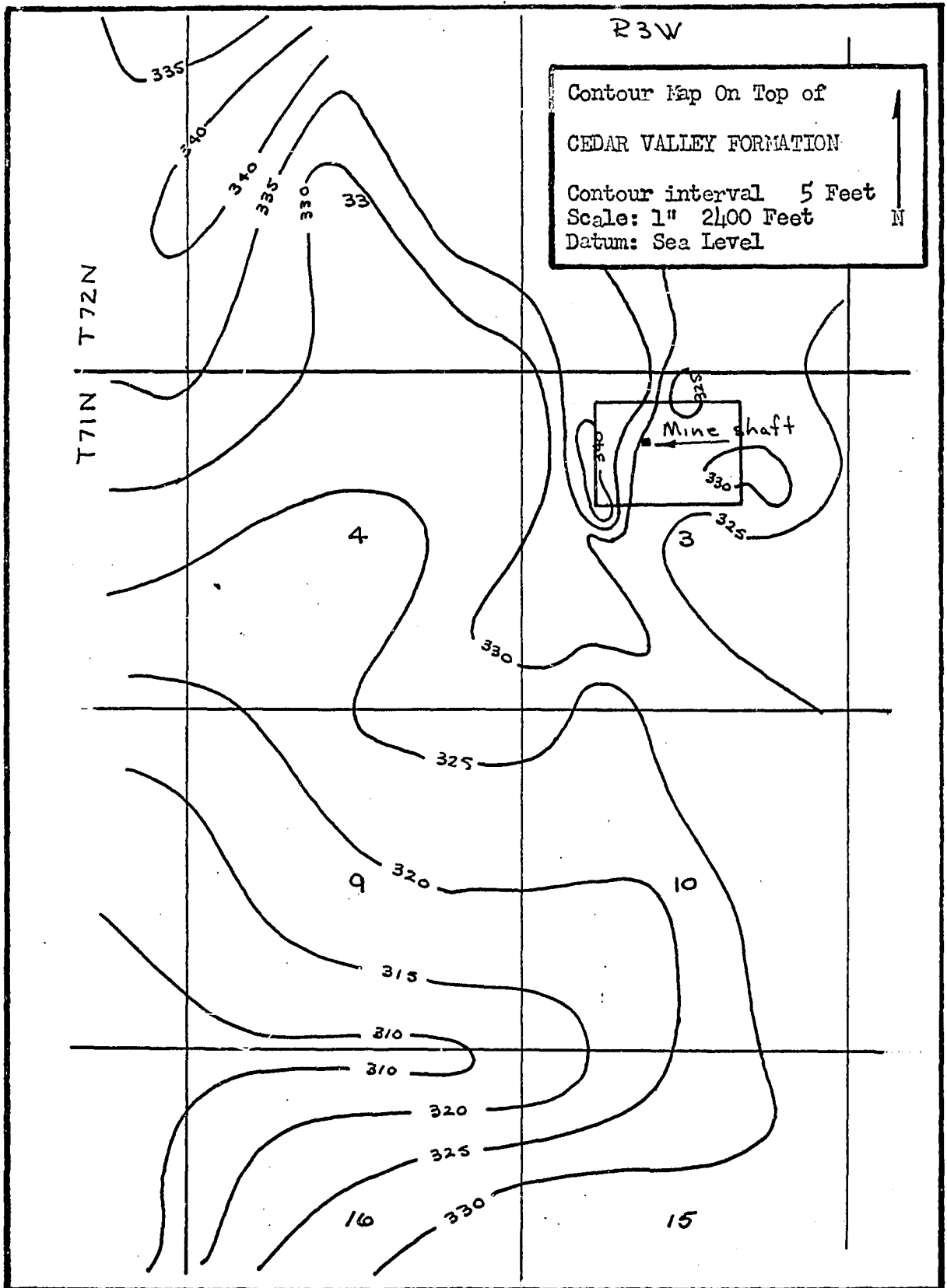
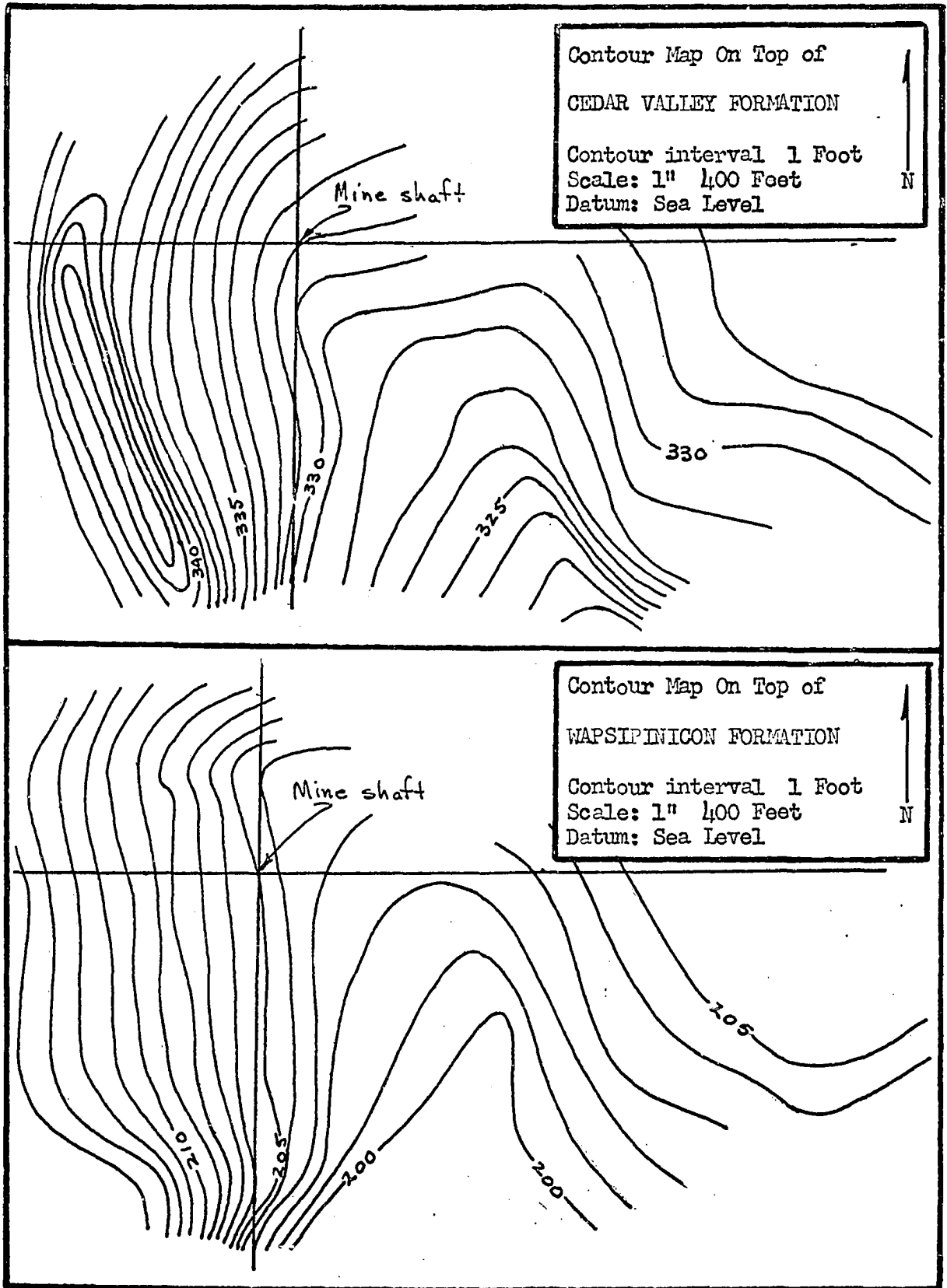


Figure 10. Detailed structure contour map on top of the Cedar Valley formation, one foot contour interval. The area covered in this map is outlined in red in Figure 9

Figure 11. Detailed structure contour map on top of the Wapsipinicon formation, one foot contour interval. The area covered in this map is outlined in red in Figure 9. Same area as in Figure 10



GYPSUM BED

The gypsum bed occurs in the Spring Grove member approximately 3.5 meters below the top of the member. It is approximately 4.5 meters thick with the upper 3.0 meters exposed in the mine. Figure 12 represents diagrammatically a composite face displaying the various units, all of which are not present at any one location.

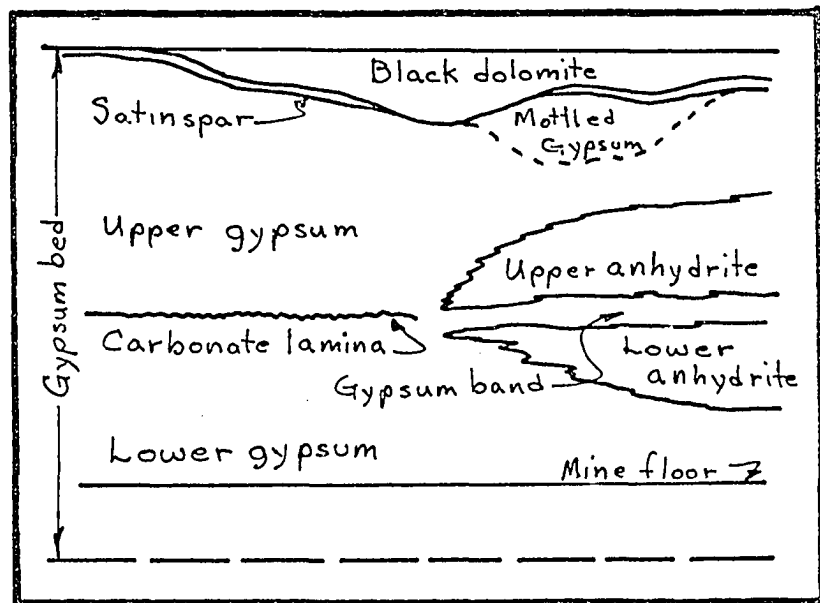
The gypsum bed is composed of two distinct units separated by a thin carbonate lamina. The upper unit is thick bedded to massive and 1.5 meters thick; the lower unit measures 3.0 meters in thickness and displays thin bedding. Anhydrite lenses occurring in the upper and lower units exhibit differences in dolomite distribution and content, and crystal texture.

The upper gypsum has lenses of black dolomite, satinspar and anhydrite, and the lower gypsum contains anhydrite lenses. Where lenses of anhydrite in the upper and lower gypsum units are adjacent they are separated by an uneven band of gypsum which occurs at the same horizon and in place of the carbonate lamina. The occurrence of the gypsum band at this horizon points up the separation plane between the two gypsum units.

Upper Gypsum

The upper gypsum is white, fine-grained, thick bedded to massive, contains small amounts of brown dolomite, and has an average thickness of 1.5 meters. In some areas a fine-grained black dolomite occurs as non-oriented, intersecting veinlets near the top of this unit. This

Figure 12. A diagrammatic sketch of the Gypsum Bed



type of structure has been described as mottled by Adams (1904). The thickness of the mottled gypsum ranges from 30 to 90 centimeters with an average of 30 centimeters.

Microscopically the gypsum in this unit is fine to coarse-grained with several distinct types of crystals of various size and shape. They are as follows:

1. Anhedral crystals less than 0.035 mm. Generally appear as a matrix to larger crystals.
2. Anhedral equant crystals, 0.035 mm and greater.
3. Anhedral bladed crystals, 0.8 x 0.09 mm.
4. Anhedral groups (crystalline groups) varying from 2.0 x 2.0 mm to 5.0 x 3.0 mm.
5. Euhedral to subhedral tabular crystals varying from 0.06 x 0.10 mm to 0.32 x 0.95 mm.

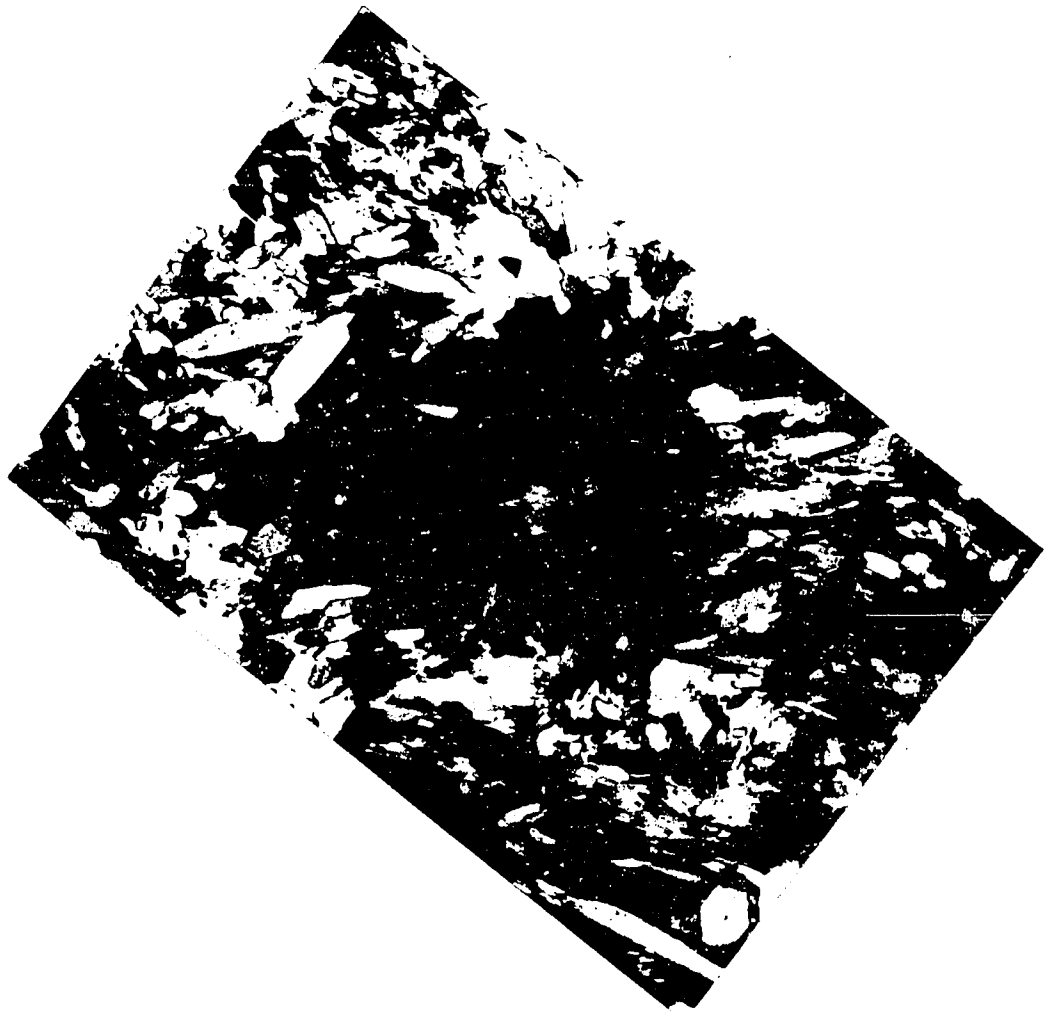
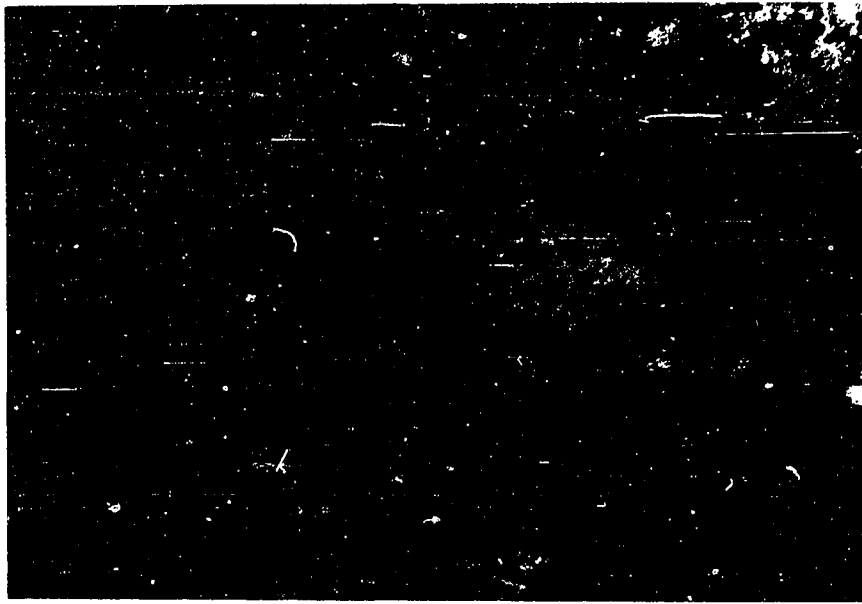
All of these occur together producing a non-oriented pattern. There is no descriptive term presently used in the literature which adequately describes the observed texture.

Large anhedral groups (Figures 13 and 14), which will be referred to in this study as crystalline groups, have been called "superindividuals" by Ogniben (1957) and "integrated gypsum" by Goldman (1952).

In thin section a crystalline group exhibits an almost uniform color at maximum illumination giving the appearance of a single crystal. Upon rotation of the microscope stage the crystalline group exhibits random extinction and its multi-crystalline nature causes the appearance to change unevenly from the uniform white color to various shades of

Figure 13. Photomicrograph of a crystalline group at maximum illumination. Enlarged 25X

Figure 14. Photomicrograph of a crystalline group (the same one as in Figure 13) rotated slightly from maximum illumination. Enlarged 25X



black and gray. To date no crystalline group has been observed with a uniform black color characteristic of extinction in a single crystal.

A preferred orientation of some crystal shapes exists locally within small areas. Small zones or clusters of bladed crystals commonly occur with their long dimensions parallel. In some instances these zones extend across the thin section, but generally they terminate within the thin section. A preferred orientation formed by alignment of bladed grains appears to exist around the periphery of some of the crystalline groups.

Euhedral to subhedral tabular crystals of gypsum occur randomly throughout the thin sections. Their euhedral form and darker outline due to relief cause them to appear more prominent than other grains of similar size. Figure 15 shows these crystals within and penetrating the boundary of a crystalline group.

Dolomite occurs in this unit as very fine-grained equant (0.15 mm) to rectangular (0.14 x 0.09 mm) crystals or in a granular form which does not exhibit well-defined euhedra.

Veins of gypsum cutting the dolomite display characteristic comb structure, transverse structure, and a non-oriented structure.

Black dolomite lenses

The black dolomite lenses are composed of fine-grained, almost lithographic dolomite containing gypsum veins and averaging 30 centimeters in thickness. They range in thickness up to one meter and in some areas are absent. The upper surface of this unit is in contact with an overlying brown dolomite along a sharp undulating interface.

The lower surface of the unit is a sharp contact with rock gypsum or a thin lens of satinspar.

Satinspar lenses

White to translucent satinspar occurs as lenses with a maximum thickness of two centimeters. They are absent in some areas of the mine but where present they show sharp contacts with the dolomite above and the gypsum below.

Upper anhydrite unit

The upper anhydrite is pale blue in color, fine-grained, massive and contains thin non-oriented veins of brown dolomite (Figure 19).

The anhydrite crystals are present in two forms:

1. Euhedral bladed (0.61 x 0.03 mm).
2. Euhedral to subhedral equant (0.04 x 0.04 mm).

Gypsum is present as large subhedral crystals (1.85 x 2.12 mm). Euhedral dolomite crystals occur as rhombs throughout the unit with the concentration of dolomite increasing downward.

The texture of the upper anhydrite is characterized by two textural elements; one element is composed of slightly bent, bladed crystals occurring in spiral-like whirls, in a matrix of smaller equant crystals; the second element contains lath-like crystals oriented with their long axes sub-parallel. The oriented groups occur as bands. These two textural elements occur together in a pattern dominated by the first element which is difficult to describe with a common textural term.

Many of the bladed or lath-like crystals of anhydrite exhibit low birefringence, parallel extinction, and low relief which are properties

similar to the optical characteristics displayed by gypsum. It was thought that these long lath-like crystals were either pseudomorphs of gypsum after anhydrite or anhydrite crystals oriented with their optic axes parallel to the axis of the microscope. In order to evaluate the above possibilities, thin sections were studied on the universal stage. The results indicated that the lath-like grains exhibiting the above mentioned properties were anhydrite.

Gypsum occurs randomly in the anhydrite matrix as large crystals (Figure 16) or along definite planes as bands or vein-like bodies ranging up to 3.6 mm in width and extending across the thin section. The vein-like bodies have been observed in hand specimens to be tabular with non-parallel sides and will therefore hereafter be referred to as veins.

The large subhedral crystals of gypsum contain segments of anhydrite crystals displaying optical continuity. The anhydrite segments are separated by the gypsum. The gypsum boundaries are generally irregular; however, some display sharp boundaries which cut individual anhydrite grains. Those gypsum crystals with irregular boundaries appear to have more anhydrite included within them than those which have well-defined faces. Bundy (1956) has reported these in anhydrite studied in Indiana and has used them as evidence of gypsum after anhydrite.

The gypsum which occurs in the veins is generally euhedral and in some a preferred orientation is observed. The veins are generally 2 mm or greater in width and extend completely across the sections. The boundaries of these bodies are irregular and can be described as jagged,

with anhydrite and gypsum crystals interpenetrating along the boundary. The line of contact between gypsum and anhydrite varies with crystal orientation of the gypsum. In general gypsum occurring as large twinned crystals truncates anhydrite crystals as shown in Figure 17. Where the gypsum crystals are small the boundary is jagged following the contour of each crystal. In many instances the vein will split into two closely spaced parallel veins which can rejoin to form a larger vein with an anhydrite inclusion.

Figure 18 shows crystalline groups directly in contact or separated from the edge of the vein by bladed crystals oriented with their long direction perpendicular to the edge of the vein. In some veins, fine-size crystals of gypsum exhibit very irregular, heavy and suture-like boundaries.

The dolomite is randomly distributed in this unit and is not abundant. Dolomite occurs in the following ways: as individual rhombs; as a granular texture composed of rhombs; and as rhombs oriented in shapes sometimes suggesting relic tabular outlines. The rhombs vary in size from 0.01 to 0.05 mm. Some rhombs occur as rims of dolomite surrounding cores of anhydrite.

Carbonate lamina-gypsum band

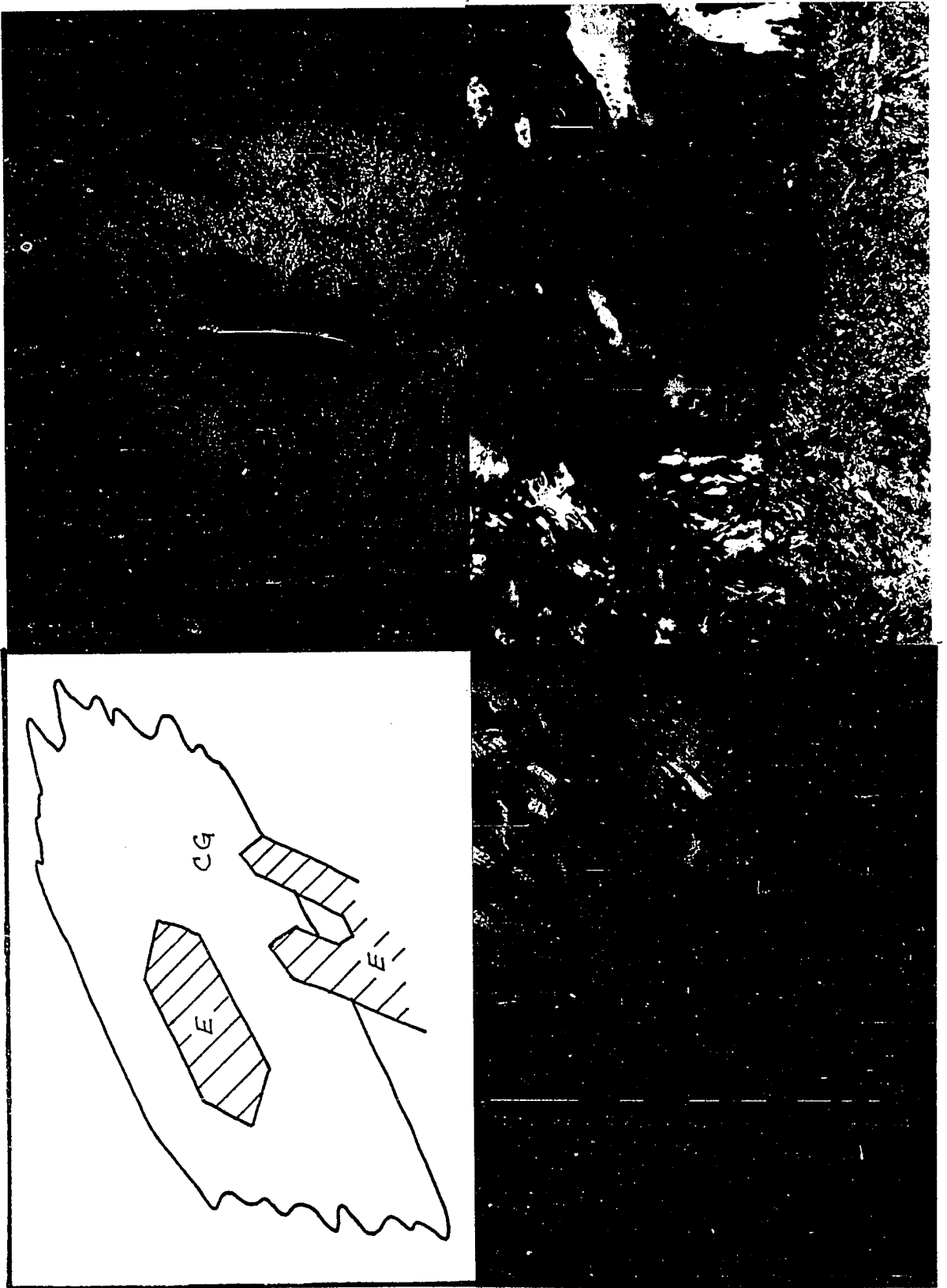
The carbonate lamina, which separates the gypsum bed into two units, is present as a brown to black carbonate material of variable thickness (1.8 to 3.3 mm), and occurs at a horizon varying from four to five feet below the roof of the mine. The lamina is composed of a fine-grained granular material, considered to be carbonate because of its high bire-

Figure 15. Euhedral gypsum crystal within
and penetrating a crystalline
group. C crystalline group
E euhedral gypsum

Figure 16. Photomicrograph of a subhedral
gypsum crystal in anhydrite.
Enlarged 25X

Figure 17. Photomicrograph of anhydrite
crystals truncated by twinned
gypsum. Enlarged 63X

Figure 18. Photomicrograph of vein gypsum
in contact with anhydrite.
Enlarged 25X



fringence, and occurs in thin veins cutting gypsum crystals or along the interface between crystals. Gypsum and traces of anhydrite crystals occur within some of the larger areas of the lamina.

Larger bladed crystals of gypsum above and below the carbonate lamina are oriented with their long dimensions parallel to each other and perpendicular to the lamina. This oriented texture does not extend more than eight centimeters above and below the lamina.

Anhydrite lenses occurring in the upper and lower gypsum units are generally adjacent but separated along a horizontal plane by a gypsum band which varies in thickness from a few millimeters up to several centimeters. The gypsum is similar to the upper and lower units except it does not contain dolomite. This gypsum is referred to as the gypsum band (Figure 12).

The carbonate lamina cuts the pseudo-folds with little or no vertical displacement, Figure 23. If displacement does occur the radius of the curved lamina is greater than the radius of the pseudo-fold.

Lower Gypsum

The lower gypsum is fine-grained, white, contains more brown dolomite than the upper gypsum, and averages 3 meters in thickness.

The brown dolomite occurs in thin, uneven laminations which range up to approximately 6 millimeters in thickness. The dolomite bands are separated by gypsum which ranges from 12 millimeters to 3.8 centimeters in thickness. The dolomite laminations are uneven and in some instances cut across the gypsum to give it a segmented appearance. This type of

structure has been termed "pinch and swell" structure by many investigators and "boudinage" (sausage-like) by Riley and Bryne (1961). Both terms, as defined, connote a genetic mechanism which may or may not be responsible for the observed structure; however, pinch and swell adequately describes the appearance of the structure and thus will be used in this study for its descriptive value only.

In thin section the lower gypsum display characteristics similar to the upper gypsum. They are as follows:

1. Anhedral crystals 0.04 mm and smaller.
2. Anhedral bladed crystals, 0.92 x 0.06 mm.
3. Anhedral groups (crystalline groups) varying from 2.0 x 2.0 mm to 3.9 x 2.6 mm in size.
4. Euhedral to subhedral crystals 0.06 x 0.10 mm to 0.32 x 0.95 mm.

The texture is exactly the same as that described for the upper gypsum and therefore will not be redescribed here. The major petrographic difference between the two units is the amount and occurrence of dolomite.

The dolomite is composed of equant euhedral rhombs varying from 0.12 to 0.02 mm in size with the average around 0.04 mm. The dolomite is cut in places by veins of gypsum which exhibit comb, transverse and non-oriented structures. Many rhombs show a corroded external boundary and some exhibit a carbonate rim with a core of gypsum. There are other rhombs which exhibit zoning of the dolomite.

Another feature observed in many thin sections, not restricted to any one unit but common in the lower parts, is a preferred orientation

of the dolomite crystals. This orientation is in the form of individual dolomite rhombs aligned to form subhedral six sided tabular bodies filled with gypsum or anhydrite, depending on the location. These tabular outlines are generally 1.2 x 0.8 mm in size. Brown (1931) observed carbonate present around individual anhydrite crystals in what he described as a "net". Stewart (1951a) shows the same feature along crystal boundaries of anhydrite, however there is no regular shape.

Lower anhydrite

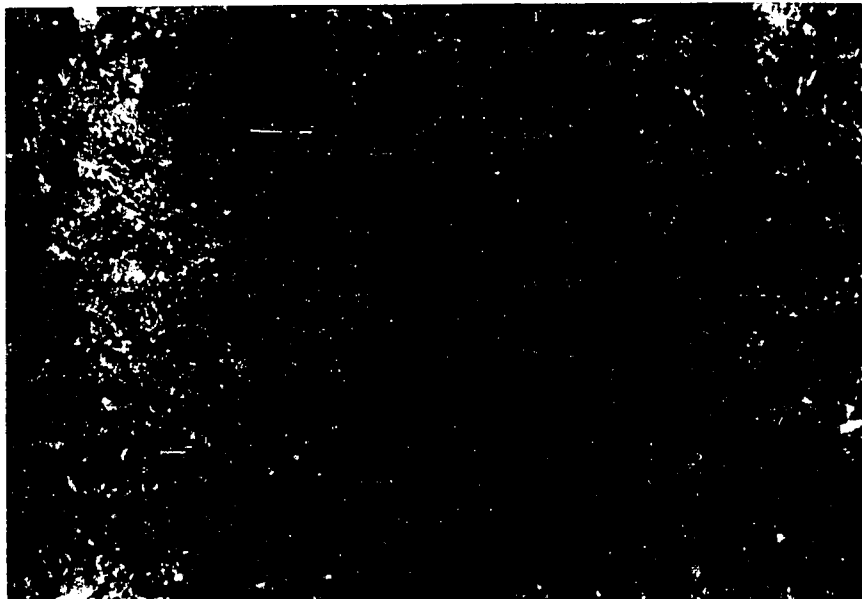
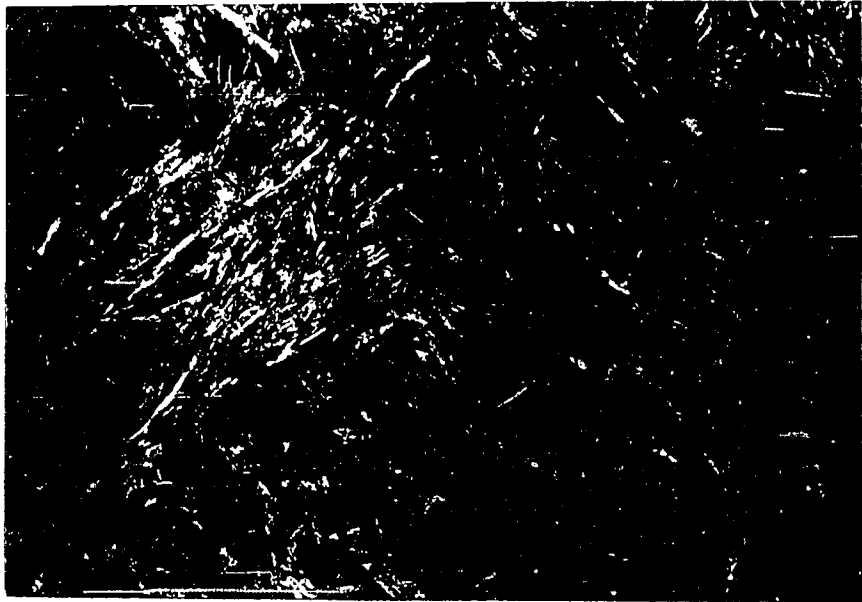
The lower anhydrite is pale blue in color, fine-grained and banded with brown dolomite (Figure 20). Maximum thickness of the lenses ranges from 15 to 61 centimeters. The brown dolomite occurs as stringers and produces laminations similar to those previously described in the gypsum unit. There is one difference; the dolomite grains occurring in the bands are not as compact as in the equivalent gypsum horizon, but are more dispersed and disseminated throughout the anhydrite.

Microscopically most anhydrite in the lower unit is composed of crystals which exhibit more of an equant or rectangular shape than the combination of lath and equant forms characteristic of the upper anhydrite lenses. This type of structure has been called "pile of bricks" structure by Brown (1931). There is more dolomite and gypsum present than in the upper anhydrite. Dolomite seems to be more abundant in the upper portion of the lense and gypsum dominates the lower portion. The anhydrite appears to differ from that found in the upper anhydrite in three ways:

1. Smaller size crystals dominate, 0.05 x 0.10 mm.

Figure 19. Photomicrograph of the upper anhydrite. Enlarged 25X

Figure 20. Photomicrograph of the lower anhydrite. Enlarged 25X



2. The crystals do not exhibit sharp faces or boundaries but instead are slightly rounded and seem to interpenetrate each other.
3. There are fewer lath-like crystals present and those that do occur show a low birefringence. Some exhibit undulatory extinction, and many are penetrated by other anhydrite crystals.

Much of the anhydrite occurs within gypsum as highly corroded and rounded crystals. Large anhedral crystals of anhydrite are present in anhydrite and dolomite.

Gypsum is found in this zone in veins or as random euhedral and anhedral crystals. This occurrence is similar to that described for the upper anhydrite and therefore will not be redescribed here.

Differences between the upper and lower anhydrite lenses are characterized by the dolomite distribution and textural variations of the anhydrite. Dolomite in the upper anhydrite lenses is non-oriented, disseminated, and of a lower concentration than in the lower anhydrite. Dolomite in the lower anhydrite lenses is located along many horizons producing irregular laminations or a banded effect. Dolomite occurring in diffuse laminae in a disseminated manner has the appearance of a finely woven net. The laminae are separated by anhydrite; however, dolomite cuts across the anhydrite and commonly connects the laminae. Textural differences of the anhydrite lenses are characterized by the presence or absence of oriented lath-like grains. The occurrence of these grains in the upper anhydrite lenses produces a gneissic structure which is notably absent in the lower unit.

Dolomite in gypsum produces a bedded effect which has a slightly different appearance than the laminations produced by dolomite in anhydrite. The concentration of the dolomite into thinner laminae in the gypsum develops a sharper contact and a darker color than the similar relationship in anhydrite. This contrast is apparent when bedded gypsum and anhydrite are observed adjacent to each other.

Internal Structures

The gypsum bed contains several types of internal structures. They are: pseudo-folds, dolomite bodies of uneven dimensions, and quartz nodules.

Pseudo-folds

The laminated gypsum, and occasionally anhydrite, does not always occur as horizontal planar features, but may be present in a knob or domical form. This structure has been called a pseudo-fold based on evidence that it is not completely formed by displacement of the laminations. The normal mechanism of fold formation requires that the components of the fold be displaced. The pseudo-folds will also be referred to as fold forms in the descriptive sense.

The shape of these forms approximates parallel or concentric folding, when observed in the mine walls, Figure 21. The fold measures approximately three feet horizontally and one foot displacement in the vertical direction; see Figure 22. In the south end of the mine the lower part of the gypsum bed is exposed and the fold forms observed in this area exhibit a gradual decrease in the magnitude of the vertical

dimension with depth. Figure 21 shows the lower-most dolomite lamination almost horizontal. The radius of the fold form increases in the upward direction creating a flatter or gentler fold form near the top of the bed; see Figure 23. The gypsum and dolomite occurring near the middle of the bed exhibit sharp fold forms which in some instances display a slightly deformed core. Deformation of this nature suggests folding by a flow mechanism; however, the laminations involved in the fold do not exhibit thinning on the limbs and thickening on the crest of the form. This type of intra-layer folding would fit into the flexural-flow class defined by Donath and Parker (1964). Most folds are not symmetrical about a vertical axial plane, and some as in Figure 23 show extreme asymmetrical tendencies.

Synclines are not associated with the pseudo-fold anticlinal form. The bedded gypsum between pseudo-folds is horizontal except when two fold forms are adjacent. In this situation the fold forms appear to interpenetrate and the base of the trough between them is an angular inflection point.

An axial trend may exist for the pseudo-folds but actual field evidence is scanty. Where observed in pillar corners the form appears domical. The fold form pattern may resemble the shapes produced by enechelon folding, with short linear features producing a knobby effect.

The fold form is very prominent in the lower portion of the gypsum bed where the dolomite content is high, but as the dolomite laminations become thinner toward the top of the bed the definition of the form decreases and in many areas is undetectable.

Anhydrite lenses which occur in the upper middle portion of the gypsum bed appear to truncate the fold forms; however, on closer inspection it becomes apparent that veins of gypsum occur in the anhydrite and parallel the fold form in the gypsum below. See Figure 24. The curved gypsum veins cutting the essentially horizontal anhydrite lens clearly demonstrate that a fold form has been developed without displacing the anhydrite. A description of this feature could not be found in the literature and therefore it is assumed that this is the first time this relationship in gypsum and anhydrite has been described.

Dolomite bodies

The dolomite bodies which occur in the mine have been grouped into two types, one of which is more abundant.

The more common type always occurs associated with the fold form. The dolomite accumulations are discordant, tabular, with their long dimension ranging from 0.3 to 3 meters and their short dimension generally less than eight centimeters, Figure 25. One edge of this tabular feature occurs near the core of the fold form and extends upward at an angle ranging from 12 to 35 degrees (an average of approximately 30 degrees) from the vertical. In one place this feature can be traced from one pillar to another; however, this is generally very difficult and if a trend does exist it is subtle. In places where this feature cuts across a lens of anhydrite, a zone of gypsum, two to eight centimeters in width, is observed between the dolomite and the anhydrite. In one instance two such bodies, one on each side, were associated with one fold form.

Figure 21. Fold form illustrating decrease in vertical displacement with depth

Figure 22. Diagrammatic sketch of fold form observed in the mine

Figure 23. Asymmetric fold form cut by nearly horizontal carbonate lamina

Figure 24. Fold form developing into anhydrite lens

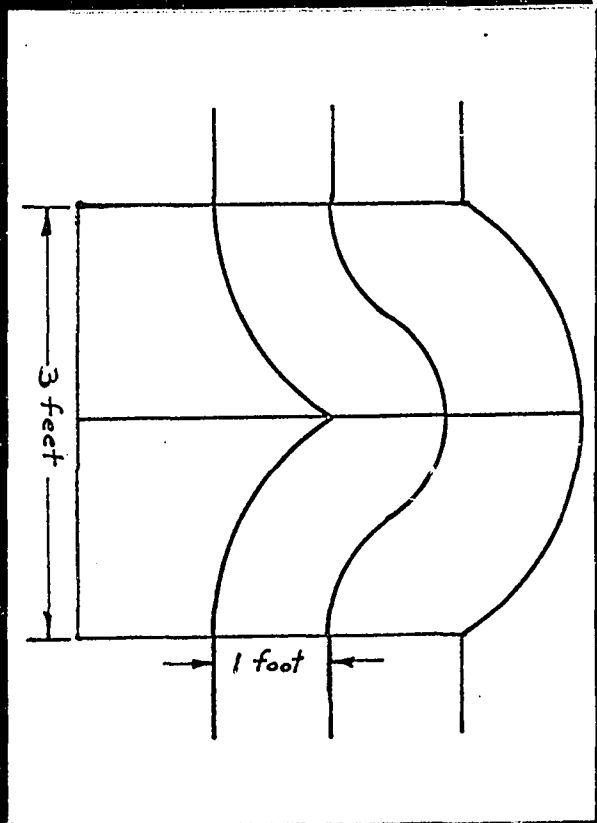
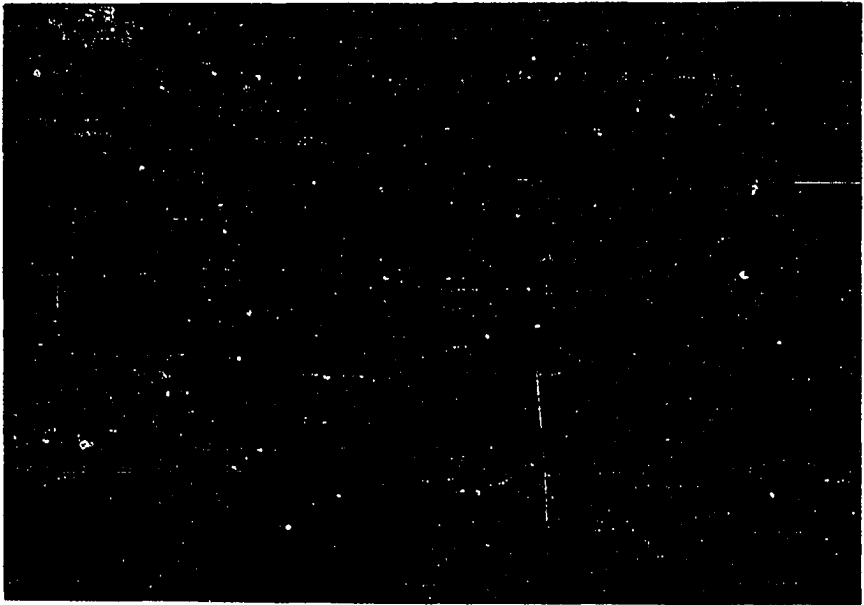


Figure 25. Tabular, inclined dolomite body



The other type of dolomite accumulation occurs randomly throughout the mine. Most of these bodies are of irregular shape - less than 60 centimeters in width, 90 to 120 centimeters in vertical height (measured from the floor of the mine) - and contain small (5 x 1 cm) solution cavities which are lined with fibrous gypsum crystals with their long axis oriented perpendicular to the sides of the cavity. The dolomite is fine-grained, light brown, saccharoidal, and has an appearance similar to the dolomite above and below the gypsum bed. Where the lower portion of these bodies occur in the unit of the laminated gypsum, laminations often carry through some parts of the dolomite body. The gypsum bands display a concave up form adjacent to the dolomite body which in appearance resembles a drag phenomenon.

The dolomite in these bodies is observed in thin section as granular fine-grained euhedral crystals and as disseminated rhombs surrounded by a matrix of gypsum. The dolomite rhombs are approximately equant and range from 0.03 to 0.07 mm in size. The granular dolomite is penetrated by vein-like bodies of gypsum which exhibit transverse and non-oriented structures. The preferred orientation of gypsum in veins is less oriented where these bodies extend into areas dominated by disseminated rhombs and gypsum matrix.

Quartz nodules

Quartz nodules which vary in size from 2.5 to 18 centimeters in diameter have been found at various localities in the mine. Only one complete nodule has been recovered intact, and this one was found on the floor of the mine after a face had been blasted. Many fragments of

nodules have been observed in the walls. The nodule recovered is sub-spherical in shape and 18 centimeters in diameter. The nodules are composed of quartz veined with gypsum and generally occur at a horizon approximately 1.2 meters below the roof of the mine. From limited observations, it appears that they occur in small groups of two to four nodules with each separated from the adjacent nodule by gypsum. The distance between nodules in a group varies from 3 to 45 centimeters and the distances between groups is measured in several meters to hundreds of meters.

The nodules are composed of crystals of quartz which range in size from 0.03 mm to 0.45 mm, with the larger crystals being subhedral and the smaller crystals anhedral. The texture varies from a mosaic for the larger crystals to granular for the smaller anhedral crystals. Euhedral shapes appear around some anhedral quartz grains as an overgrowth. Other euhedral shapes are surrounded by anhedral overgrowths of quartz. Some shapes are hexagonal and others are square and rectangular.

Gypsum occurs in the nodules in two ways: 1. as a matrix mineral between groups and individual quartz euhedra, and 2. as veins cutting through the larger quartz euhedra and fine-size granular quartz.

The gypsum which occurs as a matrix mineral appears to be filling voids because the quartz grains are idiomorphic around the periphery of the gypsum.

The veins show what might be called a low-order of preferred orientation. The crystals do not show transverse structure but instead

display larger more equant subhedral crystals in a mosaic pattern with an occasional lath-like crystal oriented perpendicular to the long axis of the vein.

DISCUSSION

The nature, origin and history of the Sperry deposit comprises its petrology. From the data gathered in this study, the mode of formation of the original rock cannot be stated. Presently the deposit is gypsum with remnant anhydrite lenses.

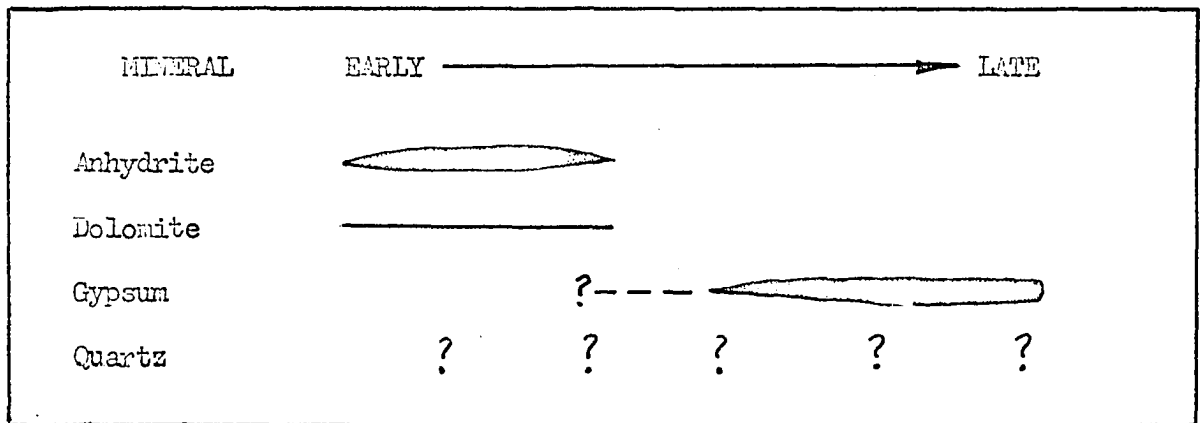
Four minerals (gypsum, anhydrite, dolomite and quartz) have been observed to occur in the gypsum bed. Their apparent paragenetic relationship is summarized in Figure 26.

Megascopic and microscopic evidence indicates that gypsum is replacing anhydrite. Replacement is taking place along the following interfaces: the upper and lower boundaries of the anhydrite lenses, the walls of veins cutting the anhydrite lenses, and within the body of the lenses along the faces of large subhedral crystals of gypsum.

Hydration of the anhydrite bed probably commenced at the upper and lower contacts of the bed and proceeded along fronts toward the middle of the bed. Lens shaped anhydrite bodies present near the upper middle portion of the bed support this hypothesis.

Laminations are absent in the upper anhydrite, yet the upper gypsum at the same stratigraphic horizon is faintly bedded. The lower anhydrite lenses are laminated by diffuse dolomite laminae whereas the gypsum at this horizon is distinctively laminated. Assuming that the physical and chemical characteristics of the anhydrite bed prior to hydration were the same as those observed in lenses in the mine, the apparent concentration of dolomite or brown material (perhaps iron oxide)

Figure 26. Paragenetic diagram of minerals observed in the gypsum bed



along definite planes may be the result of redistribution of these materials during hydration.

A statement supported by irrefutable evidence on the origin of the carbonate lamina cannot be made; however, there are two possible mechanisms of formation:

- A. The anhydrite prior to hydration was divided into two units by a separation plane at the horizon presently occupied by the carbonate lamina. The differences in the dolomite content and distribution, and textural variations of the anhydrite in the upper and lower gypsum units indicate that two separate units were present prior to hydration. The absence of the carbonate lamina between anhydrite lenses is difficult to explain by this hypothesis.
- B. The carbonate lamina may be a feature of late origin. If the "pseudo-folds" were formed by normal deformation the lamina would have had to form later than deformation. The absence of the lamina between anhydrite lenses supports a late origin, whereas, the displacement of the lamina by "pseudo-folds" refutes a late origin.

Other hypotheses can possibly be proposed on the origin of the carbonate lamina, but in light of present data it will be considered a feature controlled by the inherent differences in the two major units of the gypsum bed prior to hydration.

The origin of the fold form can only be postulated at this time. Inter-relationships of the carbonate lamina, anhydrite lenses, gypsum

veins, and the pseudo-folds suggest several possible mechanisms of formation. They are:

- A. Expansion due to hydration of anhydrite produces stress fields along which replacement of anhydrite takes place.
- B. Regional and local folding of the gypsum bed produces stress fields along which replacement of anhydrite occurs.
- C. Regional or local folding produces deformation and folding as the result of a flexural mechanism.

Two of the above (A and B) introduce a new concept of fold formation.

Following is a description of each of the above mechanisms.

- A. The following sequence is based on the assumption that hydration of anhydrite produces a volume expansion.
 - 1. Hydration of anhydrite starts from the upper and lower boundaries of the anhydrite bed.
 - 2. Certain local areas will have greater access to water along point or line sources, therefore hydration will proceed at a faster rate at these locations.
 - 3. Hydration creates greater volume change in these areas and therefore local stress fields will be developed as shown in Figure 27-b.
 - 4. Regional bending has produced tension and compression in the upper and lower portions of the gypsum bed, respectively. Therefore, there is less confining stress at the top of the bed than at the bottom. This explains the presence of fold forms only at the bottom of the gypsum bed.

5. Planes of maximum stress are developed and replacement takes place along them in both the lower and upper anhydrite units.
 6. A major shear plane occurs between 12 and 35 degrees from the vertical. Dolomite concentrates here to produce the inclined tabular bodies, Figure 25.
 7. Hydration goes to completion and pseudo-fold forms develop.
- B. The following hypothesis assumes that local bending of the gypsum bed has produced a stress field in the bed similar to that shown in Figures 4 and 27-b. Replacement of anhydrite occurs and the sequence of change will be the same as the mechanism above (A) except steps two and three which involve expansion are omitted.
- C. Normal folding may be produced by deformation of the gypsum by a flexural mechanism. The cause of deformation may be the result of regional bending of the gypsum bed, expansion due to hydration of anhydrite or excess overburden pressure causing the gypsum to flow.
1. Hydration from top and bottom of the bed will produce two layers of gypsum separated by anhydrite. The gypsum will act as an incompetent member and the anhydrite and dolomite beds will act as competent members.
 2. Gypsum, being incompetent, will yield by flexural-slip and flexural-flow and be displaced. Folds will be produced in the gypsum as hydration goes to completion.

Each of the above mechanisms may explain a part of the formation of the pseudo-folds. Replacement and deformational features are observed indicating that both mechanisms may occur; however, singly they cannot explain the formation of pseudo-folds.

Conclusions

The pseudo-folds described in this study are formed by a combination of mechanisms, including deformation and replacement.

Donath and Parker (1964) showed, Figure 2, that the relative ductility (described as competency by most authors) can be related to fold form. By referring to this figure the deformational portion of the formation of the pseudo-folds can be explained. If one assumes that the mean ductility is low for anhydrite and moderate for gypsum, and the ductility contrast is moderate between the two, the changes which occur through hydration can be related to the change in the mechanism of folding as represented by line A-B in Figure 2. Therefore as hydration proceeds the volume of gypsum and the mean ductility of the bed increase and the mechanism of deformation approaches flexural-flow folding. Evidence for flexural-flow is the asymmetrical form and the slightly deformed core of the fold forms, as shown in Figure 23.

The following sequence appears to be best supported by the available data. Expansion due to hydration of anhydrite is assumed.

1. Hydration from outer boundaries of the bed toward the middle.
2. Higher rate of expansion occurs along point or line sources due to accelerated hydration.

3. The concentration of stress due to accelerated hydration produces a stress field as shown in Figure 27-b. Figure 27-b shows the distribution of maximum and minimum stress trajectories.
4. Hydration occurring in areas of a uniform horizontal overburden stress produces horizontal laminations.
5. Expansion will produce lateral displacement of material. Movement takes place along shear planes according to the flexural-slip mechanism. The magnitude and intensity of deformation is such that the overlying anhydrite may be deformed into gentle folds by flexural-slip due to concentration of pressure as a fold form develops in the gypsum below.
6. Replacement continues along the front and also along planes of maximum stress extending into the anhydrite as shown in Figure 27-b and 27-c.
7. Major shear planes develop between 12 and 35 degrees from the vertical, and dolomite accumulates along them. Maximum shear planes would occur along trajectories bisecting the angle of intersection between the maximum and minimum stress trajectories (Figure 27-b). Figure 27-c and 27-d and the photo in Figure 25 illustrate this feature.
8. Hydration proceeds toward the middle producing pseudo-folds. The pseudo-folds later experience flexural-slip and flexural-flow folding producing shear in the limbs of the fold and a flow type deformation in the core of the fold form.

9. Hydration goes to completion and pseudo-folds continue to form.
10. The slight displacement of the carbonate lamina shown in Figure 24 can be explained by deformation due to either flexural-flow or flexural-slip after hydration is complete.

In summary, the pseudo-folds are formed partly by deformational folding and partly by replacement of anhydrite by gypsum along stress planes. Deformation may be the result of expansion upon hydration of anhydrite or regional folding with a flexural-slip mechanism.

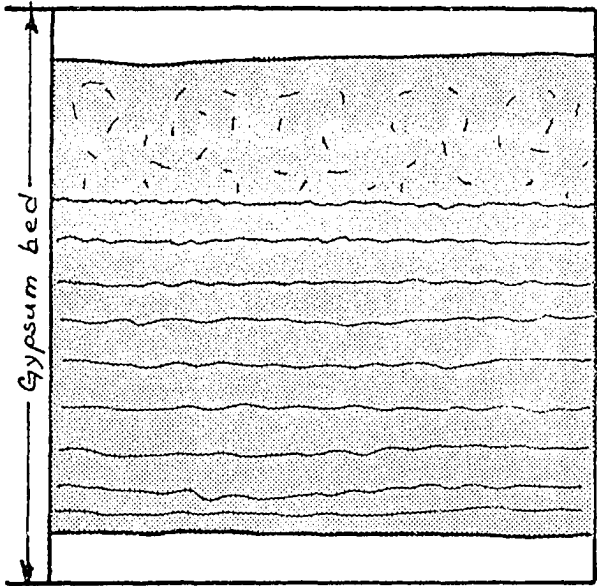
Figure 27. Hypothetical sequence of events for the hydration of the anhydrite bed and formation of the pseudo-folds

(a) Anhydrite bed prior to hydration

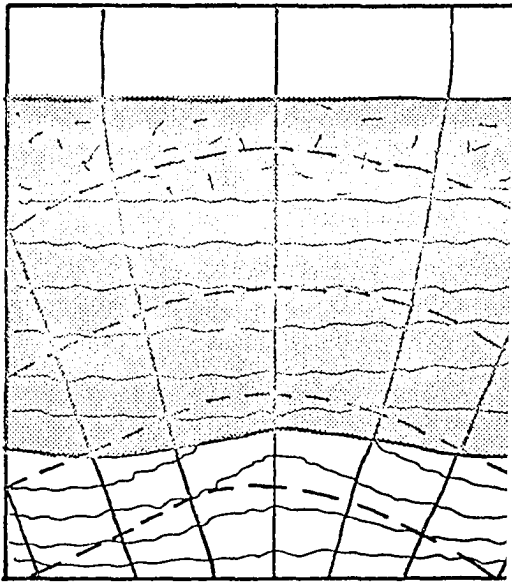
(b) Anhydrite bed partially hydrated showing maximum and minimum stress trajectories

(c) Anhydrite almost completely hydrated. Veins of gypsum occur in the anhydrite paralleling the pseudo-folds in the gypsum below. Dolomite occurs along maximum shear planes in inclined position

(d) Anhydrite bed completely hydrated to form the gypsum bed. The carbonate lamina is slightly displaced

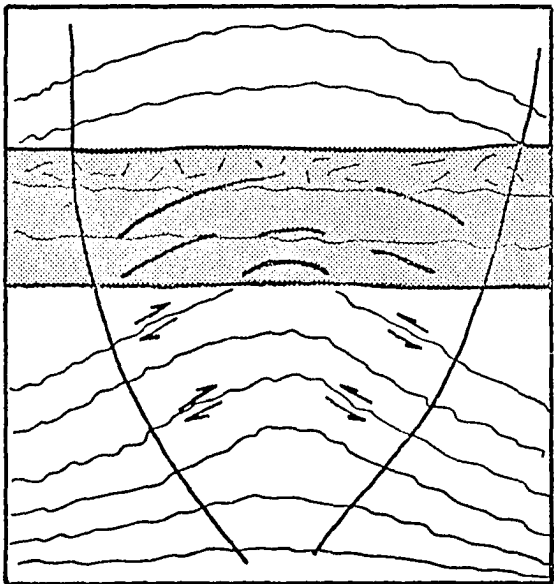


(a)

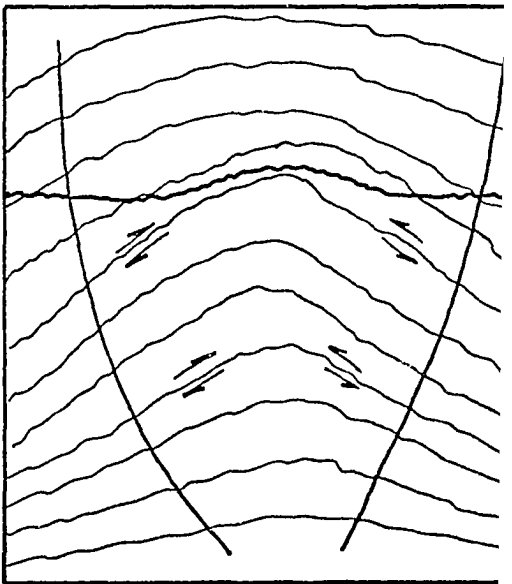


(b)







--- σ_{max}
— σ_{min}



(c)



(d)

 Anhydrite	 Dolomite laminations	 Dolomite
 Gypsum	 Disseminated dolomite	 Gypsum veins

SUGGESTIONS FOR FUTURE WORK

Problems which arose during the study can be divided into two groups: (1) studies related to better understanding of the Sperry deposit, and (2) studies of a general geological nature.

Studies of the Sperry Deposit

1. The areal distribution and stratigraphic occurrence of the Devonian Wapsipinicon gypsum should be studied to determine the nature of the depositional basin.

2. The areal distribution of the anhydrite lenses and their relationship to the local structure may indicate the pattern followed during hydration.

3. A detailed study of a single pseudo-fold should be made including:

- a. petrofabric study.
- b. stress distribution within and around the fold.
- c. areal extent and trend.
- d. shape.

4. The origin of the carbonate lamina should be investigated through a more detailed petrographic study.

General Studies

1. The mechanism which produces evaporites. In most studies on evaporites the main emphasis is placed on depositing the sediment in a certain way so as to separate the more soluble precipitates from sul-

fates and carbonates. Very little is said about what happens shortly after burial. Perhaps the chemical reorganization of these materials is more important than the mode of deposition.

2. A better understanding of the stress distribution in rock strata is needed. Perhaps simple model studies and the use of photoelastic theory may be applicable.

3. Chemical reactions which occur in stress fields are common, however, the mechanisms and the results of such a process are not understood.

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APPENDIX

Figure 7, page 14, shows the phase relationships of anhydrite and gypsum as a function of pressure, temperature and concentration of NaCl. Curves A and C represent the phase transition under equal pressure on rock and pore fluid, and the remaining two curves (B and D) show the phase transition when the pressure acting on the solid phase is 2.4 times greater (average rock density) than the pore liquid phase.

Kelly et al. (1941, p. 44) through colorimetric determinations of the heat of hydration of anhydrite, heat capacity measurements, and vapor pressure measurements determined the free energy of the reaction of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O} = \text{CaSO}_4 + 2\text{H}_2\text{O}$ to be the following:

$$\Delta G = 163.89T + 0.0215T^2 - 65.17T \log_{10} T - 2495 \quad (1)$$

where ΔG is free energy of reaction in calories per mole and T is the temperature in degrees Kelvin. When ΔG is set equal to zero, T is equal to 40°C . At this temperature gypsum, anhydrite, and pure water are in equilibrium at one atmosphere pressure.

Free energy, pressure and temperature are related by:

$$d\Delta G = \left(\frac{\partial \Delta G}{\partial P} \right)_T dP + \left(\frac{\partial \Delta G}{\partial T} \right)_P dT \quad (2)$$

where $\frac{\partial \Delta G}{\partial P} = \Delta V$ and $\frac{\partial \Delta G}{\partial T} = -\Delta S$. By setting $d\Delta G = 0$, the relation-

ship between pressure and temperature is as follows:

$$\frac{dP}{dT} = \frac{\Delta S}{\Delta V} = \frac{-135.59 - 0.043 T + 65.17 \log_{10} T}{6.66} \quad (3)$$

At a temperature of 40°C the slope of line A (Figure 7) is:

$$\left. \frac{dP}{dT} \right|_{14^{\circ}\text{C}} = 90.8 \text{ bars/deg} \quad (9)$$

For a pressure differential of 2.4, pressure on the solid phase is greater than that on the liquid phase, equations (5) and (8) can be employed to give the following:

$$\left. \frac{dP}{dT} \right|_{14^{\circ}\text{C}} = -39.45 \text{ bars/deg} \quad (10)$$

Calcium sulfate does not precipitate from natural sea water until the concentration of NaCl reaches 2.0 moles (116.8 gms) per 1000 gms H_2O . The anhydrite-gypsum transition temperature varies with concentration from 40°C in pure water to 14°C in a saturated solution of 6 moles (350.4 gms) NaCl per 1000 gms H_2O (the temperature concentration relationship is approximately linear).

In order to account for the Sperry deposit originally being anhydrite the temperature either had to be greater than 34°C for a NaCl concentration of 2.0 moles (238.6 gms) per 1000 gms H_2O or lower if the concentration was higher (i.e., at a concentration of 4.0 moles NaCl per 1000 gms H_2O the temperature could be as low as 25°C).

The temperature and pressure at deposition can probably be closely approximated but the concentration of NaCl or dissolved solids is unknown and therefore the primary origin of the sulfate deposit cannot be stated. The sulfate may have precipitated as gypsum and later, immediately below the depositional interface, converted to anhydrite as the NaCl concentration increased. If originally the concentration was high the sulfate may have precipitated as primary anhydrite.

$$\left. \frac{dP}{dT} \right|_{40^{\circ}\text{C}} = 85.4 \text{ bars/deg} \quad (4)$$

The condition of equal pressure acting on the solid and liquid phase occurs only near the surface during deposition and shortly after burial. If water has access to the crystal surfaces after burial, rock and pore water pressure will not be equal.

Assuming that rock pressure acts on the solid phase and hydrostatic pressure acts on the liquid phase the relationship between pressure and the transition temperature for the anhydrite-gypsum reaction is as follows:

$$\frac{dP}{dT} = \frac{\Delta S}{\Delta V_s + V_{\text{H}_2\text{O}}/2.4} \quad (5)$$

where ΔV_s is the difference in volumes of one mole of anhydrite and gypsum, $V_{\text{H}_2\text{O}}$ is the volume of two moles of H_2O and P is the pressure on the solid phase. The slope of line B (Figure 7) is:

$$\left. \frac{dP}{dT} \right|_{40^{\circ}\text{C}} = -39.45 \text{ bars/deg} \quad (6)$$

The effect of dissolved solids on the anhydrite-gypsum reaction can be evaluated by adding to equation (1) the change in free energy resulting from a decrease in the vapor pressure. Free energy is related to the vapor pressure by:

$$\Delta G = RT \cdot 2.303 \log_{10} p/p_0 \quad (7)$$

Equation one becomes:

$$\Delta G = 163.89T + 0.0215T^2 - 65.17T \log_{10} T - 2495 + RT \cdot 2.303 \log_{10} p/p_0 \quad (8)$$

For equal pressure acting on rock and pore phases, equations (2) and (8) can be employed to give:

The pressure, temperature and concentration can be approximated for the solid and liquid phases of the gypsum bed exposed in the mine. The rock pressure approximates 50 bars, the temperature is 18°C , and the concentration of the ground water with respect to NaCl is 0.01 moles per 1000 gms H_2O . This temperature and pressure is located on Figure 7, page 14, as a point labeled "M". Because the concentration is so low, curve B can be considered to represent the transition curve applicable to the mine.

Point "M" falls well within the gypsum stability field and therefore indicates that anhydrite present in the mine is unstable and converting to gypsum.